

RADIAL EVOLUTION OF ION DISTRIBUTION FUNCTIONS

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ABSTRACT

A survey of solar wind ion velocity distributions and derived parameters (temperature, ion differential speed, heat flux, adiabatic invariants) is presented with emphasis on the heliocentric distance range between 0.3 and 1 AU traversed by the Helios solar probe. We discuss the radial evolution of non-thermal features (e.g., $T_{\perp} > T_{\parallel}$, $\Delta v_{cp} \cong V_A$), which are observed to be most pronounced at perihelion. Within the framework of quasilinear plasma theory, wave-particle interactions that may shape the ion distributions are considered. Some results of a self-consistent model calculation are presented accounting for ion acceleration and heating by resonant momentum and energy exchange with ion-cyclotron and magnetosonic waves propagating away from the sun along the interplanetary magnetic field. Another tentative explanation for the occurrence of large perpendicular proton temperatures is offered in terms of heating by Landau damping of lower hybrid waves.

1. Introduction

The purpose of this paper is to review some experimental and theoretical work that has recently been done on the problem of the radial evolution of solar wind ion velocity distributions. We shall concentrate on Helios observations which complement previous in situ measurements at 1 AU and at larger heliocentric distances with very detailed ion measurements in the inner heliosphere between 0.3 and 1 AU. For this radial distance range average gradients of fluid parameters are now available that put further constraints on theoretical modeling of the solar wind expansion. Our results may also help to better understand the evolution of ion internal energy and non-thermal characteristics of the distributions. To date, the most detailed reviews on this subject have been published by Feldman et al. (1974) on observations of interpenetrating solar wind streams and non-thermal distributions, by Hollweg (1974) on waves and instabilities, and by Feldman et al. (1979a, b), and Schwartz (1980) on kinetic processes and microinstabilities, respectively, that affect and shape ion distribution functions. Associated plasma waves have been reviewed by Gurnett (1981) and Scarf et al. (1981). This brief paper does not aim at a complete treatment of all relevant issues but is biased towards the author's preferences. We apologize at the outset for inevitable omissions of references. An exhaustive discussion of all topics is beyond the scope of this contribution.

2. Survey of Helios observations in the inner heliosphere

The results in this section represent a selection out of a more comprehensive data set obtained by the Helios solar probes during the phase about solar activity minimum from late 1974 until the first month of 1976. A complete dis-

discussion of the present topics can be found in a series of papers by Rosenbauer et al. (1977) and Marsch et al. (1981, 1982a, b, 1983) where a full description of the data evaluation and analysis procedure is given as well as an outline of the Helios plasma instruments and measurement techniques. The magnetic field data used in this paper have been obtained by the TU Braunschweig magnetometer experiment (Neubauer et al. 1977).

The Figure 1 illustrates the variety of shapes and range of functional forms of observed proton velocity distributions encountered under various plasma conditions between 1 AU (top row) and 0.3 AU (bottom row). The three columns pertain to low ($v < 400$ km/s), intermediate speed wind (400 - 600 km/s) and fast solar wind streams ($v > 600$ km/s). The isodensity contour plots represent cuts through the distribution in a plane defined by the magnetic field vector (dashed line, axis of gyrotropy) and bulk flow direction (VX-axis). Spacing of contours corresponds to 80, 60, 40, 20 % of the maximum phase space density which defines the origin of velocity space. The "core" part of the distributions may be defined by this continuous contour line system. Broken contours are spaced logarithmically at 0.1, 0.03, 0.01, 0.003, and 0.001 times the maximum. The last contour line roughly delineates the instrument one-count level.

Apparently, solar wind proton distributions come in various shapes and as a rule deviate considerably from a Maxwellian. Most of the non-thermal features shown here have previously been observed at 1 AU by many spacecraft. Field-aligned bulges constituting a total temperature anisotropy $T_{\parallel} > T_{\perp}$ and a heat flux appear to be ubiquitous (see also Hundhausen et al. 1967, Feldman et al. 1973a) with the exception at magnetic sector boundaries (distributions A and G in Figure 1) where fairly isotropic distributions usually occur. Frequently, the heat flux tail attains the shape of a second resolved peak giving rise to a double humped ion distribution (see also Feldman et al. 1973b, 1974, Goodrich and Lazarus 1976, and Belcher et al. 1981). Double streams are temporarily also observed in the alpha particle distributions (Feldman et al. 1973b, Asbridge et al. 1974, and Marsch et al. 1982b). A statistical analysis of the speed difference between two resolved proton peaks revealed a close correlation of this drift with the Alfvén speed (Asbridge et al. 1974, 1976 and Marsch et al. 1982a, b). This observation suggests a local regulation of the differential speed by wave-particle interactions.

Inspection of the right column shows that in the core part of fast solar wind velocity distributions the temperature is larger perpendicular than parallel to the magnetic field. This finding may indicate the effects of transverse wave heating (Feldman et al. 1973a, and Bame et al. 1975) and of cyclotron resonance (Marsch et al. 1982a). Further evidence for local interplanetary ion heating in the Helios data is discussed below. In fast solar wind the protons show $T_{\perp} > T_{\parallel}$ in the core whereas for alphas one finds $T_{\perp} < T_{\parallel}$ in the central part of the distributions (Marsch et al. 1982a). This result suggests that the processes shaping ion distributions affect the various ion species in a very different manner. We also recall that in the body of high speed streams alphas move faster than protons by about the local Alfvén speed (Asbridge et al. 1976, Marsch et al. 1982b). In summary, Helios observations yield an entire "zoo" of distribution functions exhibiting various non-thermal features that become most pronounced at perihelion (0.3 AU). The association of these diversely shaped distributions with macroscopic stream structures has been investigated by Feldman et al. (1974) and in the paper by Marsch et al. (1982a), that also contains a more

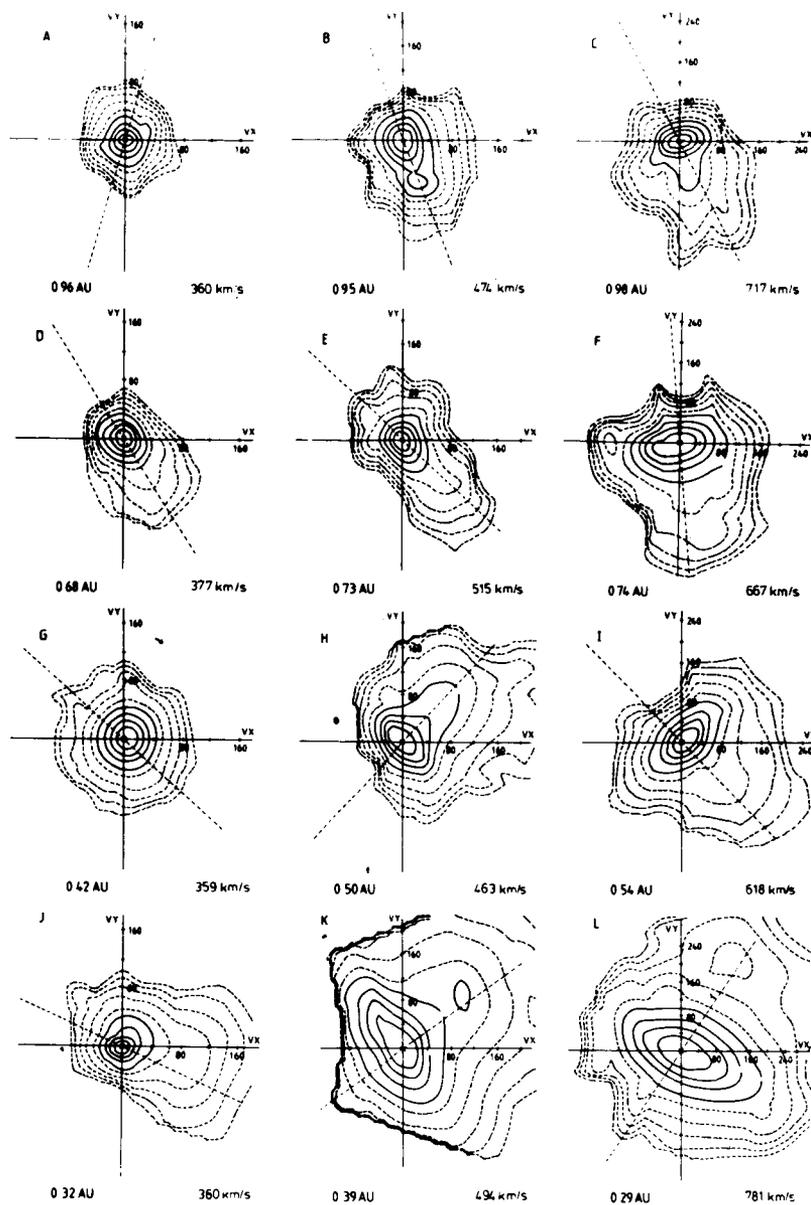


Figure 1 Helios 2 proton velocity distributions as measured for various solar wind speeds (increasing from the left to the right-hand side) and various radial distances (decreases from above to below). The cuts through the three-dimensional distributions are provided in a plane defined by the bulk velocity vector (VX-axis) and the magnetic field vector (dashed line). Contour lines correspond to fractions 0.8, 0.6, 0.4, 0.2 of the maximum phase space density (continuous lines) and logarithmically spaced to fractions 0.1, 0.032, 0.01, 0.0032, 0.001 (dashed lines), respectively. The origin of velocity space is defined by the velocity of the maximum phase space density and scales are given in km/s.

detailed discussion of double humped ion distributions and tables of relevant ion parameters. Here, we don't have space enough to discuss all these features. Therefore, in the remainder of this section we shall concentrate on the heliocentric radial temperature profiles, the so-called adiabatic invariants, and the proton heat flux density.

Before embarking on the discussion of actual data we briefly recapitulate the energy equations which are obtained for each ionic species within the framework of fluid models (Chew et al. 1956)

$$\frac{D^j}{Dt} T_{j\parallel} + 2T_{j\parallel} \underline{b} \cdot (\nabla_{\parallel} \underline{v}_j) = \frac{\partial T_{j\parallel}}{\partial t} \Big|_{w,c} - \frac{1}{n_j m_j} (\nabla_{\parallel} q_{j\parallel} - (q_{j\parallel} - 2q_{j\perp}) \nabla_{\parallel} \ln B) \quad (1a)$$

$$\frac{D^j}{Dt} T_{j\perp} + T_{j\perp} (\underline{v}_j \cdot \nabla_j - \underline{b} \cdot (\nabla_{\parallel} \underline{v}_j)) = \frac{\partial T_{j\perp}}{\partial t} \Big|_{w,c} - \frac{1}{n_j m_j} (\nabla_{\parallel} q_{j\perp} - 2q_{j\perp} \nabla_{\parallel} \ln B) \quad (1b)$$

Here the Boltzmann constant is $k_B = 1$, $\frac{D^j}{Dt} = \frac{\partial}{\partial t} + \underline{v}_j \cdot \nabla_j$ is the species' convective derivative, and $\nabla_{\parallel} = \underline{b} \cdot \nabla$ with the magnetic field unit vector $\underline{b} = \underline{B}/|B|$. The two components of the heat flux tensor are $q_{j\parallel, \perp}$ defined by third order moments. If the random velocity in the species rest frame with velocity \underline{v}_j is denoted by \underline{w} , one has $q_{j\parallel} = \langle w_{\parallel}^3 \rangle n_j m_j$ and $q_{j\perp} = \langle w_{\parallel} w_{\perp}^2 / 2 \rangle n_j m_j$ where \underline{w} brackets indicate averages over the normalized distribution function. The field aligned heat flux vector is given by $Q_j = \underline{b} (q_{j\parallel} + 2q_{j\perp})/2$. The right hand sides of equation (1a, b) comprise the heat sources due to the divergence of the heat flux tensor and also contain heating or cooling rates related to Coulomb collisions or wave-particle interactions (index c, w). Without these dissipative terms one can combine the two equations with the result

$\frac{D^j}{Dt} (T_{j\parallel} T_{j\perp}^2 / n_j^2) = 0$. By exploiting the frozen-in-field condition and the

continuity equation we can also write the double-adiabatic equations of state in the usual form

$$T_{j\perp} / B = \text{const} \quad (2a)$$

$$T_{j\parallel} (B/n_j)^2 = \text{const} \quad (2b)$$

The validity of these equations can be tested by analyzing radial profiles of ion temperatures and densities, and the gradient of the independently measured magnetic field strength along individual stream lines. The practical difficulties encountered in an experimental test of (2a, b) and the assumptions to be made in that analysis are extensively addressed in the paper by Marsch et al. (1983). Our following discussion is based on heliocentric gradients of ion plasma parameters that have been obtained by sorting the data according to the wind speed and by averaging over radial distance bins of 0.1 AU width.

The perpendicular proton temperature $T_{p\perp}$ is shown versus radial distance from the sun in Figure 2 in a double logarithmic plot for various wind velocity

classes indicated at the curves, respectively. Within a velocity class, the temperature increases with decreasing solar distance. At a fixed radial distance, $T_{p\perp}$ increases with increasing wind speed (Burlaga and Ogilvie, 1973). Note the very high temperatures of almost 10^6 °K at perihelion. Steepest gradients are observed in fast streams. Least squares-fits yield power laws $T_{p\perp} \sim r^{-a}$ with an index "a" ranging between 0.8 and 1.2. These average radial profiles are flatter than expected for an adiabatic expansion that implies $T_{p\perp} \sim r^{-2}$ for simple spherical geometry.

This result becomes more apparent by plotting the proton magnetic moment. As can be seen in Figure 3, $T_{p\perp}/B$ increases with increasing heliocentric distance demonstrating that the magnetic moment is not conserved and that adiabatic invariance is violated. Similar curves are obtained for alphas, however in fast streams ($v > 600$ km/s) the curves are almost horizontal. For protons least-squares fits yield $\mu_p \sim r^{-a}$ with $0.6 \leq a \leq 0.9$. This trend would be even more pronounced if the μ_p magnetic moment were solely based on the "core" distribution. We interpret Figure 3 as evidence that proton distributions are transversely heated in the interplanetary medium between 0.3 and 1 AU (see also Bame et al. 1975). A more complete discussion of heliocentric temperature profiles and adiabatic invariants of solar wind ions can be found in Marsch et al. (1982a, b, 1983). It should be mentioned that a recent analysis of Voyager plasma data at large heliocentric distances of several AU also provided evidence for a non-adiabatic evolution of the proton temperature and the occurrence of interplanetary heating (Gazis and Lazarus, 1982).

In Figure 4 the second adiabatic invariant of the alphas is shown versus radial distance in the same format as before. Apparently, on the average $T_{\alpha\parallel}(B/n_{\alpha})^2$ decreases during the solar wind radial expansion. Despite large scatter in the data caused by large absolute uncertainties in the measured n_{α} and by spatial inhomogeneities and temporal variations the radial trend in Figure 4 is believed to be statistically significant. This finding may be interpreted as evidence for a non-adiabatic evolution of $T_{\alpha\parallel}$, the alpha-particle parallel temperature. $T_{\alpha\parallel}$ seems to decline more rapidly than expected for adiabatic cooling. This result could well be related to the radial evolution of the ion differential velocity, which is observed to trace the Alfvén velocity (that roughly scales like $\sim r^{-1}$) and which thus decreases during the radial expansion.

In equation (1a, b) the terms giving rise to a non-adiabatic behaviour of ion temperatures are the divergence of the heat flux tensor and Coulomb or anomalous (wave-particle interactions) collisional transfer rates for $T_{j\parallel, \perp}$. For Coulomb collisions analytic expressions for "temperature exchange" between the ions can be found in the classical article by Braginskii (1965) on collision dominated transport. Observations in slow, cold solar wind indicate the possibility of an effective coupling between the various kinetic degrees of freedom for protons and alphas by Coulomb collisions (Feldman et al. 1974b, Neugebauer 1976, Neugebauer and Feldman 1979, Grünwaldt and Rosenbauer 1978, Neugebauer 1981, Marsch et al. 1981, 1982b). High speed wind data on the other hand indicate, though, that Coulomb collisions are much less important in hot, fast solar wind streams. Without invoking wave-particle interactions under these conditions there only remain the heat flux terms as a possible source of ion thermal energy.

The Figure 5 displays the proton heat flux density $Q_p = (q_{p\parallel} + 2q_{p\perp})/2$ versus radial solar distance in a semi-logarithmic plot for various solar wind velocities. Note that the variations in Q_p extend over two orders of mag-

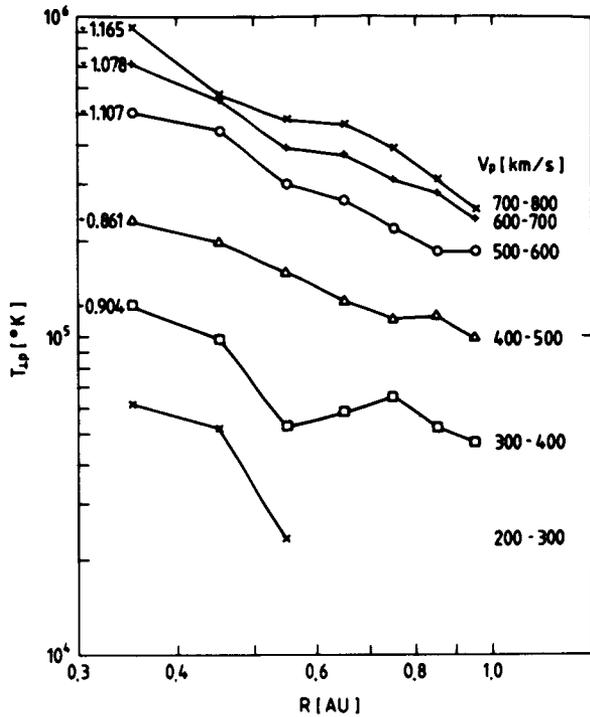


Figure 2 Average dependence of proton temperature T_p on solar radial distance for various solar wind speeds in a double logarithmic plot. Least squares fits result in a simple power law $T_p \sim R^a$ with the index a given at the respective curves.

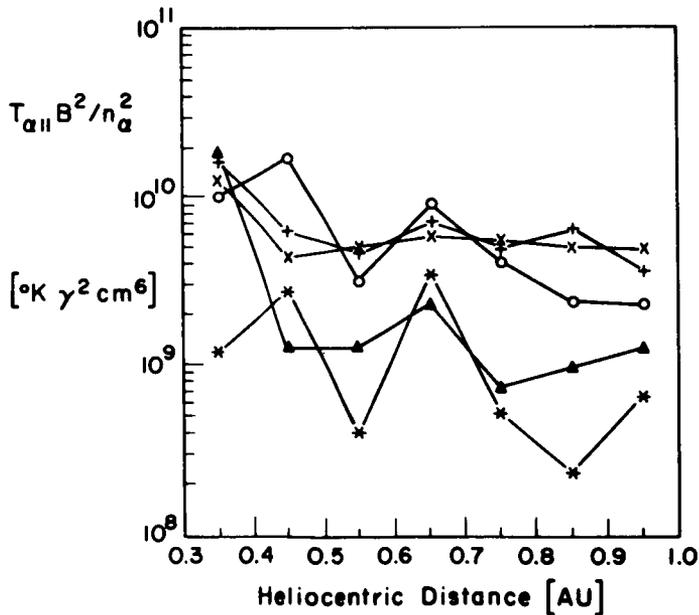


Figure 4 Second adiabatic invariant $T_{\alpha} (B/n_{\alpha})^2$ of alphas versus heliocentric radial distance for various solar wind velocity ranges indicated by the same symbols as in Figure 3.

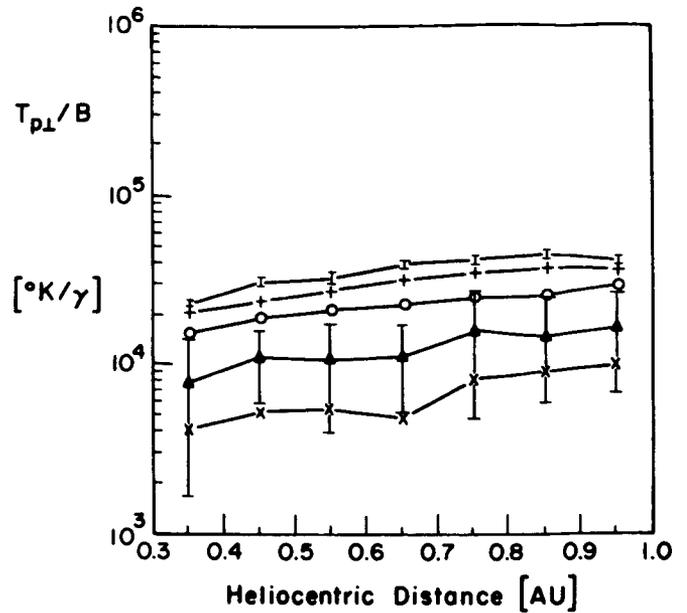


Figure 3 Proton magnetic moment $T_{p\perp}/B$ versus heliocentric distance for various V_p solar wind velocities ranging from 300-400 km/s (bottom curve) up to 700-800 km/s (top curve). Points have been linearly connected to guide the eye. Error bars indicate the standard deviation of the mean within the respective bins.

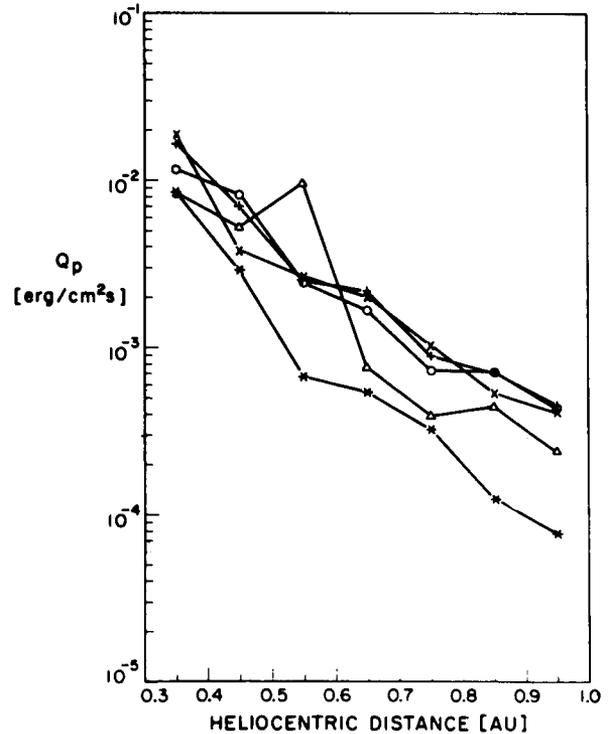


Figure 5 Heat flux density Q_p for protons versus heliocentric radial distance for various solar wind speeds indicated by the same symbols as in Figure 3. The vertical scale for Q_p is logarithmic extending over four orders of magnitude.

nitide. Between 0.3 and 1 AU Q_p ranges from several 10^{-4} to about 10^{-2} ergs/cm²s. Least squares fit yield $Q_p \sim r^{-a}$ with $3.8 < a < 4.7$ and $Q_p \sim 3-4 \cdot 10^{-4}$ ergs/cm²s at 1 AU for intermediate Q_p and high speed solar wind. Alpha Q_p particle heat flux densities turn out to be almost an order of magnitude smaller (Marsch et al. 1983) which means that $q_{\alpha, \perp}$ can be entirely ignored in equation (1a, b). For protons one finds that $q_{p, \perp}$ is much smaller than $q_{p, \parallel}$ (implying $Q_p \sim q_{p, \parallel}$). Thus in equation (1b) the terms with $q_{p, \perp}$ can also be neglected. In view of these results, one needs wave-particle interactions in order to account for the radial course of the proton magnetic moment in Figure 3. This conclusion seems to be compelling if one considers the temperature anisotropy in the high speed proton distributions of Figure 1. An anisotropic local heat source $\partial T_{j, \perp} / \partial t \Big|_w$ in terms of wave heating should be invoked to explain this detail in j proton distributions and to further explain the differences in the shapes of the alpha and proton distribution functions (Marsch et al. 1982a,b).

Concerning the parallel temperature $T_{j, \parallel}$ one can roughly estimate the strength of the interplanetary heat source represented by $-\nabla \cdot (q_{j, \parallel})$. By integrating this quantity over the radial heat flux profiles given by the j least squares fits in Figure 5, Marsch et al. (1983) found that the temperature increase resulting from a degradation of the heat flux cannot account for the non-adiabatic radial evolution of the proton temperatures. For the alphas the result of Figure 4 even suggests the need for an interplanetary heat "sink" or effective redistribution of thermal energy in order to explain the stronger than adiabatic cooling of $T_{\alpha, \parallel}$ between 0.3 and 1 AU.

We conclude with a presentation of Helios 2 data that pertain to the phase of the solar cycle inclining to solar maximum. In contrast to the typical solar minimum plasma conditions, during a few hours on day 117 in May 1978 in the perihelion at 0.3 slow solar wind was observed associated with pronounced ion differential speeds ($\Delta V_{\alpha p} \sim 100$ km/s) and temperature anisotropies ($T_{\alpha, \perp} > T_{\alpha, \parallel}$) and with unusually intense αp Alfvénic type wave activity (Marsch et al. 1981). Figure 6 shows from top to bottom proton speed, ion differential speed (Alfvén speed is indicated by points), the dot product of $\Delta V_{\alpha p}$ and \underline{B} , and the proton and alpha temperature anisotropies $T_{j, \parallel} / T_{j, \perp}$. The core αp temperature ratio is marked by points. Note the low wind j velocity. It stays low at about 400 km/s despite large Alfvénic-type velocity fluctuations. Simultaneously, the alphas move faster than the protons by more than 100 km/s. They move at about the local Alfvén speed along the interplanetary magnetic field (panel three). In the core part of the proton distribution one finds $T_{p, \perp} > T_{p, \parallel}$ whereas for the alphas the reversed situation occurs. Despite large $T_{j, \perp} / T_{j, \parallel}$ scatter in the data due to worse counting statistics, on the average $T_{\alpha, \perp} < T_{\alpha, \parallel}$ is observed. These contrary features have earlier been found to be characteristic of distributions in fast recurrent streams as discussed in Figure 1. In our opinion, this result is a key observation towards understanding the mechanism of solar wind heating and acceleration. Obviously, these ion distributions exhibited properties that have been considered typical of high speed wind originating from coronal holes during solar activity minimum. However, the unusual plasma investigated here was embedded in "normal", low speed wind. The ambient plasma showed the typical signatures of slow wind as discussed in the beginning of this section.

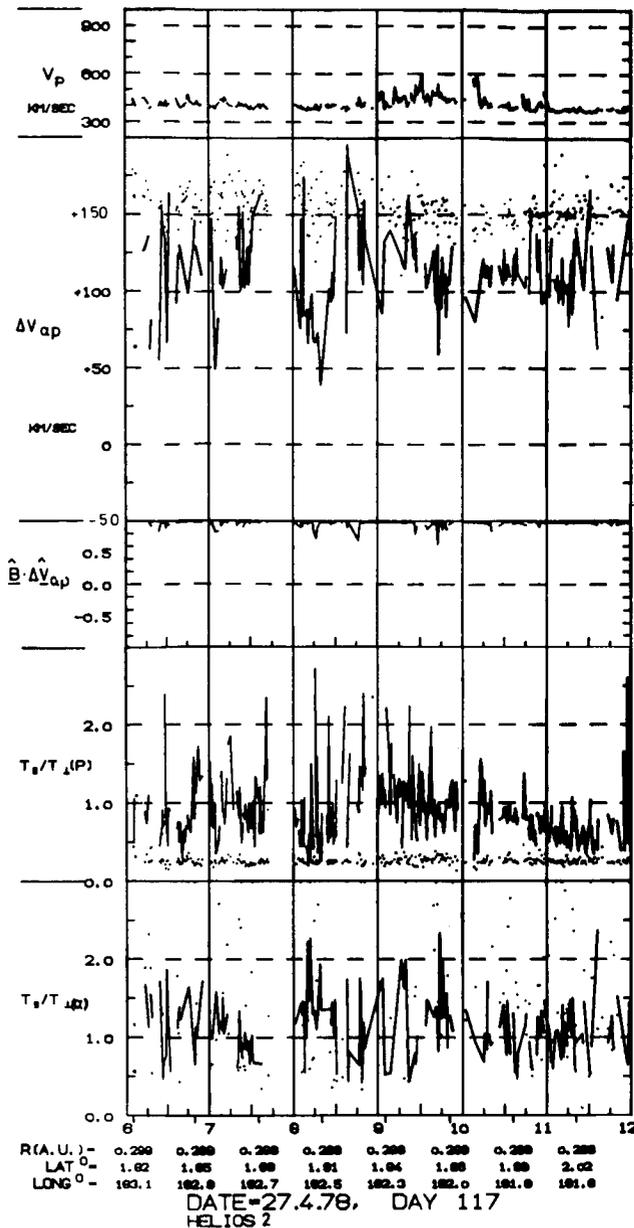


Figure 6

Six hours of Helios 2 ion data from day 117 in 1978, measured at 0.29 AU. Reading from above, the proton bulk speed, the ion differential speed (and indicated by points in the same panel, the local Alfvén speed), the cosine of the spatial angle between Δv_{ap} and the magnetic field \underline{B} , $\frac{\underline{B} \cdot \Delta v_{ap}}{|\underline{B}| |\Delta v_{ap}|}$ and finally, in the lowest panels, the proton and helium ion total temperature anisotropies are shown (the core anisotropy is marked by points).

3. Theoretical models and discussion

Certainly, the radial evolution of the detailed solar wind ion distributions cannot be explained within the framework of magnetohydrodynamic fluid theories but rather requires a kinetic treatment. Such an approach to the problem has yet not been tried. However, a vast amount of literature exists concerned with analysing the stability of distributions observed in the interplanetary medium. A comprehensive review on microinstabilities is given by Schwartz (1980) and on various kinetic aspects by Feldman (1979 a, b). A theoretical discussion of wave-particle interactions with emphasis on MHD-waves is also included in Barnes' (1979) review on wave turbulence in the solar wind.

In instability calculations particle distributions are shown to relax "locally" to a state that corresponds to less free energy than the original state. Reordering of internal ion energy is accompanied by excitation of various wave modes where growth time and dispersion characteristics sensitively depend on the shape of the actual distribution. As demonstrated in Figure 1, the main free energy sources for local wave excitation are represented by temperature anisotropies, heat fluxes and double streams, and also by the differential proton alpha-particle motion that was discussed in some detail before. Instability calculations have been performed for given this free energy in non-thermal ion distributions. However, no attempt has yet been made to explain, e.g. double ion streams in the first place by dynamic processes in the corona or during the initial phase of solar wind expansion. Feldman et al. (1974) proposed conceptual models in terms of double ion streams originating from time variations in the corona or from the interpenetration of fast into slow ambient plasma. However, these ideas are highly speculative and at present very little is understood concerning the origin of non-thermal features of ion distributions.

Goodrich (1981) investigated the kinetic effects of Alfvén wave pressure on the ion distributions. By solving the relevant diffusion equation he could show that the kinetic nature of Alfvén wave-particle interaction is reflected in distortions of the distribution function that give rise to well known fluid results like bulk acceleration. However, these model calculations are far from accounting for the detailed shape of the observed distributions. Modeling the radial evolution of ion distributions in terms of convected Bi-Maxwellians represents an intermediate step between a fluid and fully kinetic treatment. Namely, by calculating the temperatures and speeds relative to the solar wind frame one readily knows the structure of the distribution functions that are entirely specified in terms of their moments. Such model assumptions have almost universally been adopted for plasma instability calculations.

Along these lines Marsch et al. (1982c) have developed a self consistent fluid-type model in order to explain the ion temperature anisotropies and differential speeds by means of wave heating and acceleration of solar wind ions by cyclotron resonance with ion-cyclotron and magnetosonic waves propagating away from the sun along the interplanetary magnetic field. Local temperature and momentum transfer terms based on the quasilinear expressions for wave-particle interactions in weak electromagnetic turbulence (see also Dusenbery and Hollweg, 1981, and McKenzie and Marsch, 1982) have been employed in the fluid equations. It was shown by Marsch et al. (1982c) that the magnetosonic waves are capable of accelerating the minor ions to differential speeds of the order of the local Alfvén speed. Furthermore, it was demonstrated that interaction with ion-cyclotron waves can lead to an equalization of ion thermal velocities and the observed anisotropy of proton temperatures in close qualitative accord with the observations.

However, the required wave intensity exceeds the values observed (at 0.3 AU) by at least one order of magnitude, which is a serious problem all theories are faced with that rely on resonant wave-particle interactions at about the ion gyro-frequencies (Schwartz et al., 1981). This problem might be circumvented by invoking a cascade process from the low frequency Alfvén waves to the resonant frequency regime (Isenberg and Hollweg, 1982) in order to replenish the intensity at higher frequencies. Still, the physics of tapping the energy reservoir of Alfvén waves by a cascade remains rather obscured. In addition, the assumption of rigid model

distributions in the quasilinear expressions represents another problem since the plasma may in reality not conform to these model constraints simply by changing the shape of the distribution function. This effect can be crucial in case the interactions take place in the tails of the distribution. Using real distribution functions measured on Helios, Dum et al. (1980) showed that for the ion acoustic mode and whistlers the growth and damping characteristics depend rather meticulously on the detailed shape of the particle distributions. At present a fully kinetic treatment of the problem is still lacking, although it appears to be needed for an explanation of the radial evolution of ion distribution functions.

Finally, we briefly mention an alternative explanation of the large perpendicular ion temperatures in terms of Landau damping of lower hybrid waves. Marsch and Chang (1983) have demonstrated that the broad band low frequency electrostatic noise frequently observed in the disturbed solar wind at interplanetary shocks (Coroniti et al., 1982; Kennel et al., 1982) and in high speed solar wind streams (Beinroth and Neubauer, 1981, and Gurnett et al., 1979) may generally have a lower hybrid component. These modes accompanied by "hybrid-like" whistler waves can be excited by resonant halo electrons in the heat flux tail of the electron distribution (Rosenbauer et al., 1977; Feldman et al., 1981). Model calculations based on convected Bi-Maxwellian electron distributions (Marsch and Chang, 1983) have shown that electromagnetic lower hybrid waves at several $\omega_{LH} = \sqrt{|\Omega_e \Omega_i|}$ can energize solar wind ions transverse to the magnetic field, since these waves propagate almost perpendicularly. By means of Landau damping of lower hybrid waves the proton distributions could thus attain large perpendicular temperatures in the core. Furthermore, the effective coupling between protons and suprathermal electrons, being simultaneously in Landau resonance with the waves, should be of major importance for understanding solar wind transport and the regulation of the electron heat flux.

4. Conclusions

In this paper we have discussed some selected aspects of the radial evolution of ion velocity distributions that exhibited collisional and collision-less behaviour. In slow, cold, and dense solar wind there is evidence for a collisional redistribution of internal ion energy (see also review by Neugebauer, 1981). In contrast, high speed ion distributions indicate significant influence of waves that render the solar wind expansion non-adiabatic. Various processes shaping ion distributions by means of microinstabilities and models that attempt to describe the radial evolution of internal ion energy have been proposed in the literature. Two basic lines, that a theoretical description of the solar wind expansion in principle could follow, are sketched in Figure 7. The standard fluid approach has widely been used in many theoretical papers at this conference (see also the "SW4" review by Cupperman, 1981). However, very little work has been done in terms of kinetic equations (Griffel and Davis, 1969, and Eviatar and Schulz, 1970) that are solely appropriate to describe the radial evolution of detailed ion distributions and internal energy and to take dissipation properly into account. At present, observational knowledge is far ahead of a coherent theoretical understanding of solar wind microprocesses and transport. Therefore, a kinetic description of solar wind ions that incorporates collisions and wave-particle interactions is urgently required.

THEORETICAL DESCRIPTION OF THE SOLAR WIND EXPANSION

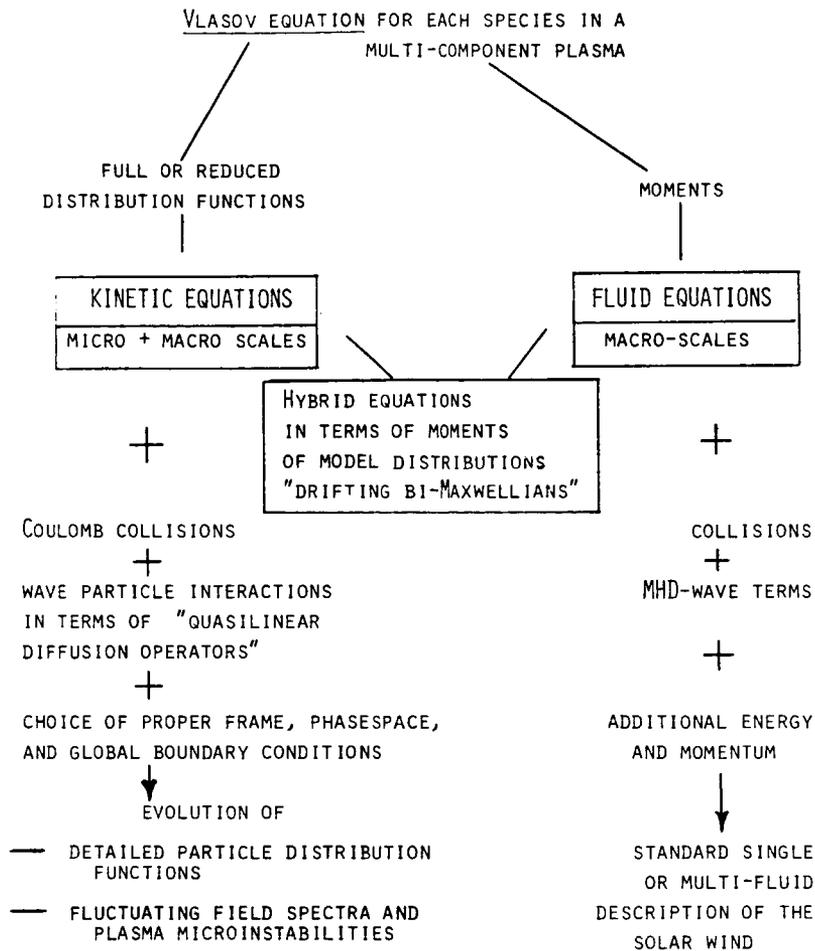


Figure 7 Schematic sketch of two possible basic approaches to a theoretical description of the solar wind expansion.

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